LOW-NOISE, CROSSED-FIELD DEVICES SUCH AS A MICROWAVE MAGNETRON HAVING AN AZIMUTHALLY-VARYING AXIAL MAGNETIC FIELD AND MICROWAVE OVEN UTILIZING SAME

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of U.S. patent application Serial No. 10/417,655, filed April 17, 2003 and entitled "Low-Noise, Crossed-Field Devices Such as a Microwave Magnetron, Microwave Oven Utilizing Same and Method of Converting a Noisy Magnetron to a Low-Noise Magnetron."

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

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BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to low-noise, crossed-field devices such as microwave magnetrons, microwave ovens utilizing same and crossed-field amplifiers.

2. Background Art

The noise generation mechanisms of linear electron beam devices are well known. Generally, fluctuations of cathode electron emission excite space charge waves, which propagate along the electron beam. Calculations and computations of noise figures in linear devices agree with experiments. Methods of noise suppression in linear tubes are at a very advanced stage. On the other hand, noise generation mechanisms in cross-field devices are not presently

understood and predictive computational calculations do not exist. Methods of noise suppression in crossed-field devices have not previously been practically realized.

Existing magnetrons and crossed-field amplifiers use an azimuthally-symmetric, axial magnetic field, shown in Figures 1a and 1b. In a standard microwave oven magnetron such as the magnetron, generally indicated at 70, of Figure 7, permanent magnets 72 generate about 1 kGauss on the face, resulting in about 1.7 kGauss on-axis, at the midpoint between the two magnets 72. The magnetron 70 also typically includes a microwave output post 73, a magnetic metal yoke 74, cooling fins 75, a vacuum envelope 76 which contains cavities, a metal box containing chokes 77 and electrical cathode/filament connections 78. Such standard noisy magnetrons generate a copious amount of microwave noise near the carrier and more widely-spaced sidebands, as shown in one of the data plots of Figure 5.

As described by J.M. Osepchuk in the 1995 article entitled "The Cooker Magnetron as a Standard in Crossed-Field Research," PROCEEDINGS OF THE FIRST INTERNATIONAL WORKSHOP ON CROSSED-FIELD DEVICES, Ann Arbor, Michigan, Aug. 15-16, 1995, University of Michigan, "The existence of magnetron noise is assuming a very practical aspect. There are over 200 million microwave ovens in the world operating at 2.45 GHz. There also are plans for a wide variety of new 'wireless' services to operate with frequency allocations ranging from 1.5 GHz to 3.0 GHz and possibly even higher, especially at 5.8 GHz. There are some serious questions about the potential that some of these systems will encounter unacceptable interference from microwave ovens – *i.e.*, the sideband noise. Thus the characteristics of microwave oven noise are being studied extensively and there are plans for interim and final (tighter) specifications to limit such noise through regulations originating in current activities of the CISPR community within the IEC (International Electrotechnical Commission). Because the noise is predominantly at low anode currents most of the time, microwave oven noise shows up as sub-millisecond pulses of noise. Some experts believe modern digital and spread-spectrum communication techniques can live with this. On the other hand, if discrete spurious signals show up especially at close to peak current, the RFI might not be tolerable. The magnitude of the peak noise or spurious in the worst cases is

of the order of 100 dB above a pW as measured in a 1 MHz bandwidth or even higher (or similar numbers in units of μV/m as measured at 3 meters from the oven). At present some authorities are investigating peak limits near such levels along with limits 30 to 40 dB lower when using narrow video bandwidths (*e.g.* 100 Hz) to yield 'average' measures of the noise."

As further described in the above-noted article, "Cooker magnetron noise, therefore, will attract regulatory pressure in the future at the same time that others, *i.e.*, the DOE in the U.S., are pressuring for higher oven efficiency which is, in principle, associated with higher noise. At the same time there are other magnetron-driven ISM devices that may amplify the concern about noise, *e.g.*, the microwave 'sulfur' lamps, that are very efficient light sources that some day may operate for many hours per night illuminating large areas in buildings and parking lots, etc. One can presume that users of magnetrons may be forced to find ways of reducing such noise. Otherwise, competing devices might for the first time in history pose a threat to the magnetron as the power source of choice for ovens and other power applications. In the past year there was the preliminary report of an efficient (67%), low voltage (600 Volts) multi-beam klystron suitable for microwave oven use. Its developers estimate that in three years problems of cost, size and weight might be resolved. The klystron poses no noise problems and has other advantages. One can expect controversial discussions of competing power sources at meetings such as those of IMPI (the International Microwave Power Institute)."

Since the above-noted article was written, several communications systems have developed in the unlicensed, 2.4 GHz radio spectrum:

1) cordless telephones operating at 2.4 GHz;
2) Bluetooth, a wireless communication system used for computers, which operates with a spread spectrum, frequency-hopping, full-duplex signal; and
3) IEEE 802.11 b and 802.11 g, a Complementary Code Keying-Orthogonal Frequency Division Multiplexing system used for computer Local Area Networks (LANs), operating in the frequency range from 2.4 GHz to 2.4835 GHz.

Since these communication systems occupy the same region of the spectrum utilized by microwave ovens, there exists significant potential for interference from noisy magnetrons.

U.S. Patent No. 4,465,953 issued to Bekefi uses a magnetic configuration which modulates the radial magnetic field by an azimuthally, spatially-periodic array of magnets in a smooth bore (no cavities) coaxial diode to generate free electron laser radiation.

U.S. Patent No. 3,932,820 issued to Damon et al. discloses how the noise in a crossed-field amplifier output is reduced by providing a non-uniform magnetic field across the surface of a cathode. A curved magnetic field may be provided across the cathode or by providing a concave shaped cathode. Additionally, the cathode may be tilted with respect to the crossed magnetic field.

U.S. Patent No. 4,709,129 issued to Osepchuk discloses a typical microwave power source for a microwave oven in which a microwave magnetron is supplied simultaneously with filament heater power and with anode voltage through an inductive reactance power supply.

U.S. Patent No. 6,437,510 issued to Thomas et al. discloses a crossed-field amplifier or magnetron which has a cathode body portion and an anode which cooperates with a crossed magnetic field to maintain emitted electrons on cycloidal paths and amplify an input signal or develop a microwave or millimeter wave output signal in an interaction space.

U.S. Patent No. 4,310,786 issued to Kumpfer discloses a magnetron electron discharge device preferably for use in microwave heating or cooking apparatus which has a cylindrical resonant anode structure surrounding a concentric electron emitting filament.

SUMMARY OF THE INVENTION

An object of the present invention is to provide cost-effective, simple, low-noise, crossed-field devices such as a microwave magnetron, a microwave oven utilizing same, and crossed-field amplifiers by the use of an azimuthally varying, axial magnetic field.

In carrying out the above object and other objects of the present invention, a low-noise, crossed-field device is provided. The device includes an electrical circuit for generating a radial electrical field, and a magnetic circuit for generating an axial magnetic field substantially perpendicular to the radial electric field. The magnetic circuit includes at least one permanent perturbing magnet having an azimuthally varying magnetic field impressed thereupon so that the axial magnetic field is azimuthally varying to substantially eliminate noise in the device.

The at least one permanent perturbing magnet may be magnetized with a number of periods of magnetic field variation.

The device may be a multi-cavity microwave magnetron including a cathode for emitting electrons and an anode having a number of resonant cavities. The cathode and anode may define an interaction space therebetween wherein interactions between electrons emitted from the cathode and the electric and magnetic fields produce a series of space charge spokes that travel around the space in an azimuthal direction. The number of periods of magnetic field variation may be based on the number of resonant cavities to shorten start-up time of the magnetron.

The microwave magnetron may be a plasma processing magnetron or may be an oven magnetron.

The microwave magnetron may further be a lighting magnetron or may be an industrial heating magnetron.

The device may be a crossed-field amplifier including an input for receiving an input signal to be amplified within the device and an output for carrying an amplified signal from the device.

The amplifier may be a radar amplifier.

The device may be a microwave magnetron having startup and peak power phases, and the noise may be substantially eliminated independent of magnetron current.

The device may be a linear crossed-field amplifier including a cavity region, and the magnetic field may vary in a direction of electron drift in the cavity region.

The device may be a microwave magnetron including one of a plurality of mode control devices such as strapping and rising sun geometries, or a coaxial cavity magnetron.

A typical magnitude of azimuthal variations of the axial magnetic field may be approximately 30%-50%.

Further in carrying out the above object and other objects of the present invention, a microwave oven is provided. The microwave oven includes a compartment, and a low-noise, oven magnetron for generating microwaves in the compartment. The magnetron includes an electrical circuit for generating a radial electrical field. The circuit includes a cathode for emitting electrons and an anode having a number of resonant cavities. The cathode and the anode define an interaction space therebetween. A magnetic circuit generates an axial magnetic field substantially perpendicular to the radial electrical field in the interaction space. Interactions between electrons emitted from the cathode and the electric and magnetic fields produce a series of space-charge spokes that travel around the space in an azimuthal direction. The magnetic circuit includes at least one permanent perturbing magnet having an azimuthally varying magnetic field impressed

thereupon so that the axial magnetic field is azimuthally varying in the interaction space to substantially eliminate noise in the device.

The at least one permanent perturbing magnet may be magnetized with a number of periods of magnetic field variation.

The number of periods may be based on the number of resonant cavities to shorten start-up time of the magnetron.

Still further in carrying out the above object and other objects of the present invention, a low-noise, microwave magnetron is provided. The magnetron includes an electrical circuit for generating a radial electrical field. The circuit includes a cathode for emitting electrons and an anode having a number of resonant cavities. The cathode and anode define an interaction space therebetween. A magnetic circuit generates an axial magnetic field substantially perpendicular to the radial electric field in the invention space. Interactions between electrons emitted from the cathode and the electric and magnetic fields produce a series of space charge spokes that travel around the space in an azimuthal direction wherein the axial magnetic field has a number of periods of perturbations in the azimuthal direction in the interaction space based on the number of resonant cavities to substantially eliminate noise and shorten start-up time of the magnetron.

The microwave magnetron may be an oven magnetron.

The magnetic circuit may include at least one permanent perturbing magnet having an azimuthally varying magnetic field impressed thereon.

Yet still further in carrying out the above object and other objects of the present invention, A microwave oven is provided. The microwave oven includes a compartment, and a low-noise, oven magnetron for generating microwaves in the compartment. The magnetron includes an electrical circuit for generating a radial electrical field. The circuit includes a cathode for emitting electrons and an anode having a number of resonant cavities. The cathode and the

anode define an interaction space therebetween. A magnetic circuit generates an axial magnetic field substantially perpendicular to the radial electrical field in the interaction space. Interactions between electrons emitted from the cathode and the electric and magnetic fields produce a series of space-charge spokes that travel around the space in an azimuthal direction. The axial magnetic field has a number of periods of perturbations in the azimuthal direction in the interaction space based on the number of resonant cavities to substantially eliminate noise in the magnetron and shorten start-up time of the magnetron.

The magnetic circuit may include at least one permanent perturbing magnet having an azimuthally varying magnetic field impressed thereupon.

The above object and other objects, features, and advantages of the present invention are readily apparent from the following detailed description of the best mode for carrying out the invention when taken in connection with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1a is a side schematic view of a prior art oven magnetron including its magnetic configuration;

FIGURE 1b is a top view of the magnetron of Figure 1a;

FIGURE 2a is a side schematic view of an oven magnetron including magnets for generating an azimuthally varying axial magnetic field in its magnetic configuration;

FIGURE 2b is a top view of the magnetron of Figure 2a;

FIGURE 3 is a top schematic view of a magnetron including coils for generating an azimuthally varying axial magnetic field constructed in accordance with a second embodiment of the present invention;

FIGURE 4a is a side schematic view of an upper (or lower) magnet of a magnetron including magnetic pole pieces constructed in accordance with a third embodiment of the present invention;

FIGURE 4b is a bottom view of the magnetron magnet of Figure 4a;

FIGURE 5 are graphs of signal amplitude versus frequency for a prior art oven magnetron and an oven magnetron of the present invention;

FIGURE 6 is a sectional, top schematic view of a microwave oven including a magnetron of the present invention;

FIGURE 7 is a side schematic view of a conventional magnetron which may be noisy, showing upper and lower annular, permanent magnets and which may be used in a conventional microwave oven;

FIGURE 8a is a side schematic view of a microwave magnetron with an upper permanent magnet magnetized with high (H) and low (L) regions of magnetic field to generate an azimuthally-varying axial magnetic field and optimized for an 8-vane magnetron; and

FIGURE 8b is a top view of the magnetron of Figure 8a.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In general, low-noise, crossed-field devices such as a microwave magnetron and microwave oven utilizing same are disclosed. In a first embodiment of the invention, at least one permanent magnet is added to the existing magnetron magnets to cause the axial magnetic field to vary azimuthally. This embodiment of the invention is depicted in Figures 2a and 2b, in which four permanent magnets 10 have been added to one of the prior art magnets 12 (either upper or lower). Each magnet 10 has a strength of 3.0 to 4 kGauss on their face. The added permanent magnets 10 are located with their magnetic poles opposing (or adding to) the axial

direction of the field of the standard, azimuthally-symmetric magnetron magnets 12. It is not crucial that the perturbing magnets 10 be exactly the same size or magnetic field, nor that they be symmetrically located around the periphery of one of the standard magnets 12. The perturbing magnets 10 perturb the axial magnetic field of the magnetron or crossed-field amplifier.

Figure 5 shows the experimental data of microwave spectra, in which a noisy, standard magnetron without the invention (*i.e.*, Figures 1a and 1b) has been compared to a magnetron with the magnetic configuration of a first embodiment of the present invention (*i.e.*, Figures 2a-2b). It can be seen that the first embodiment of the invention completely eliminates the noise and sidebands in the oven magnetron of Figures 2a-2b.

Figures 3 and 4a-4b show alternative apparatus of generating azimuthally varying axial magnetic field for a magnetron (or crossed-field amplifier).

In general, in order to generate an azimuthally varying axial magnetic field, a number of different embodiments are possible, including, but not limited to:

1) permanent magnets;
2) shaped magnetic pole pieces; or/and
3) shaped coils or multiple coils.

Figure 3 is a top view of a second embodiment of the present invention wherein a large magnetron coil or magnet 30 creates a main axial magnetic field. Small coils 32 generate the azimuthally varying axial magnetic field.

Figures 4a and 4b are side and bottom views, respectively, of a third embodiment of the present invention wherein magnetic pole pieces 40 generate an azimuthally varying axial magnetic field. The pole pieces 40 are coupled to an upper (or lower) magnetron magnet 42.

Figures 8a and 8b are side and top schematic views, respectively, of a low-noise, microwave magnetron with permanent upper magnet 80 magnetized with high (H) and low (L) regions or periods of magnetic field to generate an azimuthally-varying axial magnetic field. A lower magnet 82 is substantially the same as in Figure 2a. However, it is to be understood that the lower magnet 82 may be magnetized like the upper magnet 80. The magnetron may be a 8-vane magnetron and the magnetron is optimized for the 8-vane magnetron as described in detail hereinbelow.

The startup of the magnetron is hastened by introducing an optimal number of azimuthal variations in the axial magnetic field. For an N-cavity magnetron operating in the pi-mode, this rapid startup may be achieved if the number of maxima in the axial magnetic field is N/2 in the azimuthal direction. (The number of minima of the axial magnetic field is also N/2 in the azimuthal direction.) The physical reason for this magnetic field arrangement is that when the magnetron is turned on, the electron orbits immediately move into an N/2 fold symmetry which favors the excitation of the pi-mode, long before this internal electromagnetic mode appears. These electrons, favorably grouped into a N/2 fold symmetry, naturally speed up the excitation of the pi-mode in this case.

Computer simulations (2-dimensional) have been performed to demonstrate the rapid startup of magnetrons with azimuthally varying axial magnetic fields. In the simulations, the number of cavities is $N = 6$. To encourage rapid excitation of the pi-mode, an $N/2 = 3$ fold symmetry is imposed in the axial magnetic field. The axial magnetic field thus reads, for this example,

$$B = B_o [1 + (\alpha/2) \sin (3\theta)]$$

where B_o is the mean axial magnetic field, α is the magnitude of the maximum azimuthal variation (θ-variation) of the axial magnetic field (in fraction of the mean magnetic field) in the 3-fold symmetry. Results of these simulations are compared to an unperturbed (uniform) magnetic field with $\alpha = 0$ and a perturbed magnetic field with $\alpha = 0.3$

In the unperturbed magnetic field case, the electrons in the Brillouin hub showed no special feature early in the magnetron pulse. In the perturbed case, the electrons clearly began to form 3 bunches, the desired number of bunches for pi-mode operation in a 6 vane magnetron. The formation of these 3 electron bunches is due solely to the 3-fold azimuthal symmetry in the external axial magnetic field, long before the pi-mode is excited.

Still early in the magnetron pulse, for the unperturbed axial magnetic field, the electrons still showed no special feature. In particular, they showed no significant bunching nor the much desired 3-fold symmetry. By contrast, in the perturbed magnetic field, the electrons developed 3 well defined bunches that began to lift off the cathode hub and to approach the cavities.

Later, the electron positions for magnetrons showed bunching in the unperturbed magnetic field case. By contrast, in the perturbed magnetic field case, the electron spokes were fully developed and extended well into the magnetron cavities; it is expected that microwave oscillation would begin to develop at this time.

The simulations demonstrate the rapid startup may be extended to other configurations and designs:

A. Magnetrons with other numbers of cavities.

B. Operation with other modes than the pi-mode.

C. Adjustment of the strength of the azimuthal variation (α) in the external magnetic field.

D. In general, for operation of a magnetron mode with $\exp(j\omega t - jm\theta)$ dependence, where ω is the angular frequency of the mode and m is number of the azimuthal variations of this mode, rapid startup of this mode will be achieved by introducing m azimuthal variations of a suitable magnitude in the external magnetic field.

Figure 6 schematically shows a microwave oven including a cooking chamber or compartment of the present invention. The oven includes an oven magnetron of the present invention coupled to the chamber for generating microwaves therein. The oven also includes a power supply for the magnetron as well as timing controls. The oven further includes a door and a fan as is well known in the art.

The low-noise, crossed-field devices have application to reducing interference with telephone and computer communications by microwave magnetrons in microwave ovens.

Magnetrons are also used for lighting and industrial heating and the noise-free magnetrons of the present invention are applicable in these areas.

The efficiency of magnetrons would also be improved for applications which require a precise microwave frequency, such as plasma processing.

Another important application of the invention is the reduction of noise in crossed-field amplifiers utilized for the Department of Defense. This could lead to higher signal-to-noise ratios and better resolution for radars.

The invention reduces the noise in magnetrons, both during the critical startup phase and in the peak power phase. The reduction of noise is independent of magnetron current. Microwave noise is reduced in both new magnetrons and older, noisy magnetrons.

This invention extends to a linear crossed-field amplifier in which the transverse magnetic field varies in the direction of the electron drift in the cavity region.

This invention also applies to magnetrons that employ mode control devices such as strapping and rising sun geometries, as well as coaxial cavity magnetrons.

The typical magnitude of the azimuthal variations of the axial magnetic field are in the range of 30%-50%.

While embodiments of the invention have been illustrated and described, it is not intended that these embodiments illustrate and describe all possible forms of the invention. Rather, the words used in the specification are words of description rather than limitation, and it is understood that various changes may be made without departing from the spirit and scope of the invention.